High-Performance-Computing (HPC) Enhancements to Military Research

by

James L. O'Daniel, James T. Baylot, Robert L. Hall
U.S. Army Engineer Research and Development Center (ERDC)
Vicksburg, MS

Abstract

The ERDC Geotechnical and Structures Laboratory (GSL) conducts experimental and analytical research studies to improve the safety of both military and civilian personnel housed in conventional structures exposed to the effects of explosive attacks by terrorists. The GSL also supports the military mission planning needs of our warfighters. High-performance computers available at the ERDC Major Shared Research Center (MSRC) coupled with Computational Structural Mechanics (CSM) software developed under the HPC Modernization Program (HPCMP) Common HPC Software Support Initiative (CHSSI) have significantly enhanced the research programs conducted at the GSL for the military. High-Performance-Computing enhancements to three military research efforts conducted by the GSL are discussed in this paper. Scalability of the software on the HPC system utilized in this study is also addressed.

Introduction

The GSL is the lead laboratory for research in the Civil Engineering area of survivability and protective structures (S&PS) under the Tri-Service Project Reliance Civil Engineering Science and Technology Plan. The S&PS research program is focused on the warfighter's needs for force protection and counter-terrorist threats. The ERDC is conducting anti-terrorism research for the U.S. Army Research Development Test and Evaluation (RDT&E) program on Force Protection from Terrorist Threats, the U.S. Interagency Technical Support Working Group (TSWG), and the U.S. Department of State. The ERDC has assisted the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) in developing fast, accurate methods of predicting damage to both steel and concrete bridge beams. These methods were needed for computer programs that are used to plan air attack missions on bridge targets.

Pre-event simulations were performed for experiments conducted for the RDT&E program, TSWG, and the State Department. The response of concrete masonry unit (CMU) walls (commonly known as concrete block walls) was studied for both the RDT&E program and for TSWG. These simulations were used to assist in designing and understanding the experiments. A retrofit means of reducing the hazard behind windows was being developed by the State Department. In these experiments, multiple simulations were performed to assist in designing the retrofits being tested. Data on the response of bridge beams to conventional weapons are extremely limited and it is impractical to conduct enough experiments to develop a method of predicting that response. Therefore, simulations using an experimentally validated method were used to numerically develop a database. Over a hundred simulations were required to account for the number of combinations of weapon type, weapon location, and weapon orientation needed. These simulations were possible due to the resources available through

HPCMP. Fast-running, accurate models for predicting the response of bridge girders were developed.

Analysis Software and Scalability

All of the simulations presented in this paper were performed using the HPCMP CHSSI CSM finite element (FE) code, ParaDyn (Hoover, DeGroot, and Pocassini, 1995). ParaDyn is the scalable version of DYNA3D (Whirley and Engleman,1993). The ParaDyn scalable algorithms are designed to divide the problem mesh into sub-domains. Solutions on sub-domains are connected together by communicating data across processors along the boundaries of the sub-domains. A pre-processing code takes the original entire mesh and attempts to balance load among processors by assigning elements to each of the processors. Shared nodes along boundaries are duplicated in all processors containing elements attached to those nodes. Most of the analyses were performed using the 128 processor Origin 2000 available at the ERDC MSRC. The Origin 2000 uses the 195 MHz R10000 processors. Later analyses and the scalability studies were performed using the 512 processor Origin 3000 available at the ERDC MSRC. The Origin 3000 uses the 400 MHz R12000 processors.

Code scalability was evaluated for two significantly different problems. The first was one of the simulations needed to develop the model for predicting the response of concrete bridge girders to conventional weapons. Details of the analysis are presented later. The model consists of approximately a million constant stress continuum elements configured into a 30-ft by 30-ft by 2-ft-thick target model. Pressure boundary conditions are applied to the surface exposed to the conventional weapons to represent fragment impacts. The identical simulation was conducted using 2, 4, 8, 16, 32, 64, and 128 processors of the Origin 3000.

The second simulation used to evaluate scalability was one of the CMU block analyses. In that simulation a one-block wide model of a CMU wall is modeled. The model is 19 blocks tall and each layer is tied together using a tie-breaking surface. Every other layer consists of two half blocks that are tied together using tie-breaking surfaces. Contact surfaces such as these significantly affect partitioning and scalability. Therefore a scalability study was also performed for this type of problem. The model consisted of about 49,000 nodes and 29,000 continuum elements. Each of the simulations was identical except for the number of processors used. Because of the small number of nodes and elements involved, scalability beyond 32 processors was not evaluated.

The results of the scalability studies are shown as Figures 1 and 2. The computational time shown is the maximum processor time used by any of the processors. The actual performance is compared to ideal scalability. For each case, the ideal scalability curve was determined by dividing the time required for two processors by the number of processors used and then multiplying by two to get scalability related to a single processor. The closeness of the actual curve to the ideal curve indicates very good scalability for the bridge beam problem. Although scaling between two and four processors is good, scaling beyond four processors is not as good for the CMU problem. For perfect scaling, the time required for the simulation should be inversely proportional to the number of processors. The speed factor shown in Figure 2 is the time required for a single processor (taken as twice the time for two processors) divided by the time required for the number of processors under consideration. This figure demonstrates that even in a linear-linear plot, the actual performance for the bridge beam problem was very close to the ideal performance. Again, scaling is not as good for the CMU problem.

Load balancing is critical to scalability in this problem. Load balance was evaluated by computing the difference between the maximum (processor that used the most time) and minimum (processor that used the least time) processor for each simulation. That number was then divided by the minimum processor and multiplied by 100 to obtain an estimate of the maximum imbalance. The imbalance is listed in Table 1. As seen in this table, the load balance is extremely good for both the bridge beam and CMU wall problems. The worst imbalance for the bridge beam problem occurs when 64 processors are used and that error is only 8.44 percent. Thus the maximum processor time is only 8.44 percent higher than the minimum processor time. The worst imbalance for the CMU wall problem is for the 16 and is only 4.76 percent. Using the optimum number of processors was critical to obtaining the turn-around time needed to successfully complete the large number of analyses needed for this project. Using the optimum number of processors made it possible to complete pre- and post-experiment analyses in time to effectively support the experimental programs.

Table 1 Load Balance Error

Number of Processors	Load Balance Error, percent	
	Bridge Problem	CMU Problem
2	0.006	0.41
4	0.043	0.22
8	0.0069	1.94
16	0.143	4.76
32	0.080	1.26
64	8.44	
128	1.24	

Response of CMU Walls to Blast

The Army RDT&E Program on Force Protection from Terrorist Threats funded the development of an HPC method of predicting the response of concrete masonry unit (CMU) walls to blast. The method must be capable of predicting failure and failure velocity of the debris resulting from failure. In the method developed (Dennis, Baylot, and Woodson, 2000), each block (Figure 3) is discretized into continuum elements. Each block is tied to the neighboring blocks using a tie-breaking interface. Once the tie-breaking interface is broken, the interface behaves as slide-surface, preventing inter-penetration of the blocks and allowing them to slide with friction on each other. Simulating the mortar joint with these tie-breaking surfaces allows the simulation to continue efficiently beyond failure of the wall so that the debris velocity can be predicted. The methodology was used to perform pre-experiment analyses to assist in designing a series of experiments for TSWG. The pre-experiment analyses for a one-way un-grouted CMU wall (mortared top and bottom) are presented in Figure 4. Analyses were performed to determine the combination of pressure and impulse required to fail the wall for two different charge weights. Several analyses had to be performed to determine each point on each curve. For example, at a given value of peak pressure, the impulse was increased by increasing the peak duration. The analyst made an educated guess at the duration required to just fail the wall. He performed the simulation, and adjusted the duration for the next simulation based on the results of that simulation. He continued this process until he had converged on the boundary between failure and survival. The multiple simulations required to develop the curves of Figure 4 would not have been practical without the scalable ParaDyn code.

Five experiments were conducted for the CMU wall geometry tested in the TSWG program. The pre-experiment predictions were used to select the charge weight and standoff used for the experiment and were used to adjust the standoff in the remaining experiments. The model correctly predicted a low hazard level in three of the five experiments. In one of the experiments, the model correctly predicted a high hazard level. Post-experiment computed and measured debris velocities are shown as Figure 5. The response mode (Figure 6) compares very well with that taken from high-speed video of the experiment. Post-experiment analyses are identical to pre-experiment analyses except that blast pressure gage measurements are used as the loads. In the other experiment, the model predicted a high hazard level when only an intermediate level occurred. That experiment was conducted at the same charge weight and standoff as the one that caused a high hazard.

The analysis methodology has been modified to allow for more realistic boundary conditions and to improve the modeling of grout-filled and reinforced CMU walls. Simulations were performed to assist in conducting 43 experiments for TSWG. In the new series of experiments, there was a gap between the top of the wall and the top of the reactions structure. Un-grouted, partially-grouted, fully-grouted, reinforced, and non-reinforced walls were tested. Several retrofit techniques were also evaluated. High-performance-computing simulations were used to assist in designing these experiments. In this series, experimental damage ranged from minor cracking to failure at a high velocity for each construction type. The data obtained are being used to validate the analysis methodology. The GSL, in conjunction with the National Science Foundation Engineering Research Center at Mississippi State University, is enhancing this methodology to improve grid generation, add more boundary condition types, improve partitioning, include window and door openings, and to better model reinforced walls.

Window Retrofit Design

The U.S. Department of State is currently retrofitting various government buildings to provide better protection against blast load environments. A major concern is upgrading the structural integrity of the windows and their support structures in order to prevent the damage and injuries caused by flying pieces of failed windows. A vertical blind concept, consisting of vertical steel slats attached to the floor and ceiling, designed to catch the glass after it had been blown out of the window, failed while being tested. The connection system was not robust enough to withstand the desired loading level and failed for most of the vertical blinds.

Determining the structural integrity of such systems against blast environments primarily through experimentation has become unfeasible due to the rising financial and manpower costs of conducting experiments. Simulations can greatly augment the design and analysis process. Physics-based simulations can also find details about the behavior of the structure under investigation that cannot be discovered during an experiment. Finite element codes allow for a number of systems and geometries to be modeled and varied relatively quickly at a much lower cost than actually testing each design.

Finite element models of the vertical blind system were developed to perform analysis and provide design recommendations. Initially, the failed connection system was reproduced numerically, and then new designs were numerically analyzed in order to determine several connections that would withstand the desired blast-loading environment. Models of the retrofit system were simplified by only simulating a single vertical blind and its connections to the floor and ceiling. A symmetry plane at the mid-height of the blind was used to further reduce the model size. A representative version of a simulated vertical blind is shown in Figure 7, consisting of the blind itself, a "yoke" connection system, and a c-section to attach the connection to the floor or ceiling. Both two-dimensional thin shells and three-dimensional hexagonal solid elements were used to model different parts of the vertical blind system. The actual blind was always modeled using shell elements, as were any of the c-sections that were used in the connection. The remainder of each connection was modeled with a combination of solid and shell elements.

An initial parametric study was performed on the blind to determine an appropriate mesh refinement. The element density in the blind was systematically increased until an error of less than one percent occurred between iterations of the simulation. This type of parametric study is essential in determining the extent of the mesh and how many elements are needed to accurately determine the response of the system in question.

After numerically reproducing the failure mechanism of the original vertical blind connection, finite element simulations were used to provide several redesigns of the system that would withstand the required loading environment. Multiple design types were modeled, and their structural integrity determined. The following typical design process was followed for each design type.

1. An initial design was provided, modeled, and subjected to the predetermined load levels.
2. The simulated structural response of the design was observed, and a failure mechanism (if one was present) and its location ascertained.
3. Modifications were applied to the design, in response to the failure. These included, for example, thickening of the vertical blind, enlarging specific members, or adding gusset plates to the c-section.
4. The modified design was simulated and the process repeated until either the design survived under the applied loading or the design was abandoned as a not-viable alternative. Several of the modified designs were discarded as impractical.

Two final designs were arrived at after multiple iterations on approximately 10 different vertical blind system designs. These systems, a yoke connection, shown in Figure 8a, and a solid connection, shown in Figure 8b, were numerically shown to possess the structural integrity needed to withstand the desired blast loading. The figures depict the peak-deflected shape of each design and show contours of effective plastic strain throughout the system. As excessive plastic strain leads to failure of the steel, the design process attempted to minimize the plastic strain. These redesigns were constructed and successfully survived a subsequent experiment. The simulated systems exhibited deformation behavior that was very similar to the tested systems.

A typical model of the vertical blind system consisted of approximately 25,000 elements, a relatively small model. The vertical blind was modeled with 3,000 shell elements, while the c-section contained approximately 800 shell elements. In a typical model the U-bolt, plate, and large bolt were all discretized with solid elements, containing 7,500, 11,500, and 2,000 elements respectively.

These models were run on four to eight processors on the Origin 2000 system. Additional processors did not shorten run times due to the sliding interfaces employed in the model. In an attempt to partition the model onto 16 processors, DYNAPART would leave several processors without any elements, creating a model that could not be run by ParaDyn. This was due to the methodology used in DYNAPART that requires an entire interface to be placed onto a single processor.

Response of Concrete Bridge Girders to Conventional Weapons

The JTCG/ME has developed a computer code to assist weaponeers in planning missions to attack bridges. Typically the objective of attacking a bridge is to collapse a span of that bridge so that the bridge cannot be easily repaired. More than one bridge beam must be failed in order to accomplish the objective. The weaponeers may be planning many missions, using several different attack options. The attack planning software uses numerous MonteCarlo simulations to predict the probability of success of a given mission. Given the approach and number of analyses performed, the method of predicting bridge response must be fast and accurate. Typically this type of predictive methodology is developed based on experimental data. Sufficient experimental data are not available to develop this methodology.

The GSL has used ParaDyn to successfully predict damage to and the response of concrete targets to conventional weapons. The JTCG/ME tasked the GSL with performing analyses to create a weapons effect database (WEDB) that could be used to develop the needed analysis methodology. The impact of weapon casing fragments is the primary damage mechanism for concrete bridge beams. The breakup of a conventional weapon into fragments is a random phenomena. Typically, the fragmenting characteristics are determined by performing a series of experiments (arena tests) where fragment mass and velocity data are collected as a function of location around the weapon. The JTCG/ME wanted to be able to predict the response to sixdifferent weapons. Arena data were available for each of the six weapons. A computer code, FRAGPOL (Sues, Lavelle, and Rhodes, 1995) has been developed to predict a set of fragment impact conditions consistent with arena data. Arena data for the six conventional weapons of interest were installed into FRAGPOL and FRAGPOL was used to generate impact conditions on the FE model of the target. Each fragment impact was simulated using a pressure boundary condition that matched the impulse associated with that fragment.

A 30-ft by 30-ft by 2-ft thick target was selected for these analyses. The target was discretized into 1,036,800 cubical (1.5-in.) constant stress continuum elements. FRAGPOL was used to determine the impact location, velocity, mass, and angle of incidence of each significant fragment striking the target. In-house Fortran codes were used to compute the location of the impact on the FE grid and to determine the pressure history for each fragment. Once a given simulation had been performed, the results were post-processed in order to estimate the damage to the concrete beam.

Simulations were performed to model multiple fragment impact experiments (Dallriva and Davis, 1998). Damage estimates from the simulation were compared with damage observed in the experiment. These comparisons were used to calibrate the damage measure used to predict damage in the simulations performed to develop the WEDB. The experimentally calibrated and validated analysis methodology was used to predict the damage to concrete bridge beams to a range of weapon types and locations. A damage comparison for one of the experiments, Figure 9, shows that the method provides a reasonable, targeting conservative estimate of the damage to the concrete.

It was anticipated that the damage to the concrete would be a function of the weapon under consideration, the location of the weapon, and the angle of the weapon. The approach selected was to populate a database for a vertical weapon for each of the weapons. When the weapon is extremely close to the target, the fragments impact very close to each other and the damage is highly localized and severe. As the weapon is moved away, the depth of damage becomes less, but the extent of the damage spreads. Enough simulations must be performed so that it is reasonable to interpolate between simulations to develop a fast predictive method. As many as nine analyses were needed to cover the range from complete breach to only surface damage for one of the weapons. As a result of the non-linear relationship between damage and standoff, the standoffs needed were determined based on the results of previous analyses. Thus waiting for a day for a single run result would have made timely completion of the project impossible. Most of the analyses were performed using 16 processors of the Origin 2000 and were accomplished in about an hour. These runs would have taken about 40 minutes on the Origin 3000. Based on the recently conducted scalability study, two-processor runs on the Origin 2000 would have taken approximately 8 hours. An 8-hour turnaround time would have made timely completion of hundreds of runs impossible. A 1-hour turnaround time made it possible to submit a run, get the results the same day and, based on those results, submit another run. This made the timely completion of hundreds of runs possible.

It was determined that the damage to a concrete bridge beam from a vertical weapon could be represented as an ellipsoid of revolution with minor and major radii that are functions of the weapon type and standoff. A comparison of FE simulation to ellipsoid damage is shown as

Figure 10. Major and minor ellipse radii were determined as a function of range for each of the six weapons by performing the required FE simulations and interpreting the results.

Analyses were then performed to determine the effect of weapon angle on the damage to the concrete beam. The final model provides a method of determining an equivalent vertical weapon, so that the vertical weapon methodology gives a good estimate of the damage and damage location for the angled weapon. The horizontal standoff for the equivalent vertical weapon, X_V, may be represented as:

$$X_V = X_\theta / \cos(\theta)$$

where X_θ is the horizontal standoff for the weapon inclined at an angle θ from vertical. The equivalent vertical location may be obtained by offsetting the weapon vertically by an amount, Y, given by:

$$Y = X_\theta / \cos(\theta_{eff})$$

where θ_{eff} is the effective inclination angle given by:

$$\theta_{eff} = (a + b\, X_\theta + c\, |\theta|)\theta$$

where a, b, and c are determined as a best fit to FE results and are a function of weapon type and whether the weapon is angled with its nose toward or away from the bridge beam. Finite element analyses were performed at angles of 0, 22.5, 30, and 45 degree off of vertical for a single weapon standoff distance, and were performed for several different standoffs for a 45 degree weapon angle. The fit constants were determined based on these analyses and the methodology was checked by performing other combinations of angle and standoff not included in the fit runs.

The methodology was incorporated into the JTCG/ME code for predicting the response of bridges to conventional weapons.

Conclusions and Future Efforts

High-Performance-Computing simulations assisted the Army RDT&E and TSWG CMU research programs by providing pre-experiment analyses that helped to design and conduct the appropriate experiments. As a result, a database including a range of wall types over a range of response from minor cracking to high-velocity failure is available. The database is being used to further validate the analysis model so that the analysis model can be extended beyond the wall types used in the experiments. High-Performance-Computing simulations were used to fine-tune retrofits tested for the State Department. These analyses allowed a successful retrofit experiment to be conducted rather than a failed one that would have been likely in the absence of the simulations.

The analyses for the JTCG/ME WEDB demonstrate the capability of ERDC to use HPC simulations to the support the needs of the warfighter. This is a procedure that could be repeated for almost any need that the military has. In this case a limited database was used to validate an analysis methodology. That validated methodology was used to populate a numerical database which was then used to develop an engineering tool for predicting the response of bridge girders to conventional weapons.

Blast in urban terrain is an example of another analysis area where validated HPC simulations could be used to develop a tool needed by our warfighters. The military is developing tools to predict the response of structures to blast. The blast is affected by the presence of other buildings in an urban terrain. A fast method of predicting the effect of those buildings on blast is critical to supporting the military's force protection needs. It is practical to perform such simulations using the automatic mesh refinement version (Littlefield, Oden, and Carey, 2000) with rigid obstacles (Littlefield, 2001) of CTH (McGlaun, Thompson, and Elrick, 1990). Multiple-building blast load experiments being planned under the U.S. Army RDT&E program could be used to validate the HPC methodology, which could then be used to model other building configurations to build a numerical database that could then be used to develop an engineering model for predicting blast loads in an urban environment.

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Figure 1: Maximum Processor Time

Figure 2: Speed Factor

Figure 3: Finite Element Model of CMU

Figure 4: Pre-experiment Predictions

Figure 5: Comparisons with Data

Figure 6: Visual Deformation Comparisons

Figure 7: Finite Element Model of Window Retrofit

Figure 8: Deformed Retrofit Model

Figure 9: Damage Due to Fragment Impact

Figure 10: Comparison of Finite Element Model to Engineering Model